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Brief Summary of the Evolution of High-Temperature Creep-Fatigue Life Prediction Models for Crack Initiation

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INTRODUCTION

The evolution of high-temperature, creep-fatigue, life-prediction methods used for cyclic crack initiation is traced from inception in the late 1940's. The methods reviewed are material models as opposed to structural life prediction models. Material life models are used by both structural durability analysts and by material scientists. The latter use micromechanistic models as guidance to improve a material's crack initiation resistance. Nearly one hundred approaches and their variations have been proposed to date. This proliferation poses a problem in deciding which method is most appropriate for a given application. Approaches have been identified as being combinations of thirteen different classifications. This review is intended to aid both developers and users of high-temperature fatigue life prediction methods by providing a background from which choices can be made.

The need for high-temperature, fatigue-life prediction methods followed immediately on the heels of the development of large, costly, high-technology industrial and aerospace equipment immediately following the second world war. Major advances were made in the design and manufacture of high-temperature, high-pressure boilers and steam turbines, nuclear reactors, high-temperature forming dies, high-performance poppet valves, aeronautical gas turbine engines, reusable rocket engines, etc. These advances could no longer be accomplished simply by trial and error using the "build-em and bust-em" approach. Development lead times were too great and costs too prohibitive to retain such an approach. Analytic assessments of anticipated performance, cost, and durability were introduced to cut costs and shorten lead times. The analytic tools were quite primitive at first and out of necessity evolved in parallel with hardware development.

After forty years we are actively developing more descriptive, more accurate, and more efficient analytic tools. These include thermal-structural finite element and boundary element analyses, advanced constitutive stress-strain-temperature-time relations, and creep-fatigue-environmental models for crack initiation and propagation. This paper is concerned with the high-temperature durability methods that have evolved for calculating high-temperature fatigue crack initiation lives of structural engineering materials. Only a few of the methods have been refined to the point of being directly useable in design. Recently, two of the methods have been transcribed into computer software for use with personal computers (McGaw and Saltsman (1991) and Nelson, et al (1992)).

CONCEPT OF FATIGUE CRACK INITIATION

The high-temperature, life-prediction models considered in this review have been developed for fatigue crack initiation. They are material models rather than structural models. Development has been based on the behavior of smooth, axially-loaded specimens with uniform stresses, strains and temperatures. Influences of structural shape, size, and function are lacking intentionally to permit determination of underlying material rather than structural behavior.

Structural life prediction procedures utilize material life models in direct conjunction with thermal and structural analyses to quantify material response in identified local crack initiation-prone regions of a structure. The tacit assumption being that if a material's response is accurately known under well-controlled laboratory conditions, it will respond similarly within a small region of a loaded structure provided the local conditions are identical. For example, if a smooth axially-loaded laboratory specimen initiates a crack of prescribed size after 1000 cycles of repetition of a 1% axial strainrange, a structural element will also initiate the same size crack in the same number of cycles provided the local range of cyclic strain is the equivalent of the 1% axial strainrange. If the structure can tolerate appreciably longer cracks without loss of structural integrity, the additional crack propagation life cannot be estimated on the basis of knowledge from small, smooth, axially-loaded laboratory crack "initiation" specimens. Computation of the rate of cyclic crack progression at these larger crack lengths must be dealt with using the principals of fracture mechanics. However, the field of fracture mechanics has not as yet progressed to the same level of engineering utility for high-temperature, time-dependent creep-fatigue as has the field of cyclic crack initiation. High-temperature fracture mechanics methods are beyond the scope of this manuscript. The reader is referred to recent literature on the subject; see, for example, Anon. (1989).

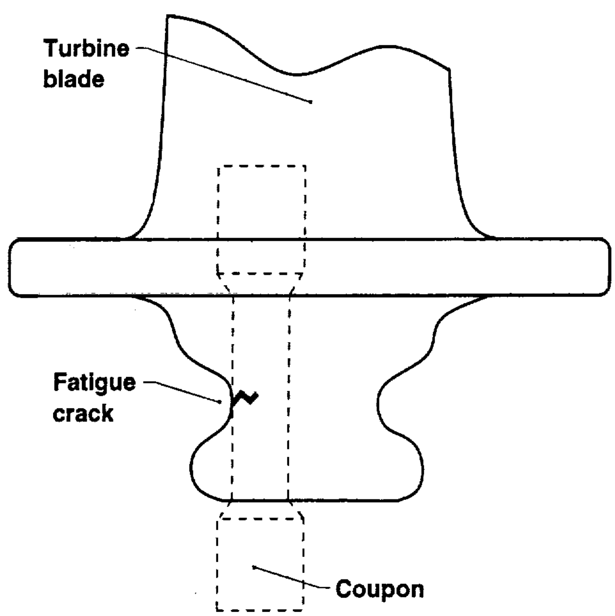

Figure 1 - Crack initiation in structural element modeled by laboratory coupon

ENGINEERING CRACK INITIATION

While the validity of fatigue crack initiation as a basic physical concept is debatable, it is, nevertheless, a powerful engineering assumption that has permitted the economic life assessment of countless structural components over the years. It is likely to remain that way for the foreseeable future, as dire needs remain for accurate engineering durability assessment of newly proposed, high-performance industrial and aerospace equipment.

The term fatigue crack initiation has considerable meaning at the engineering level. It loses this meaning as the scale of observation becomes more microscopic. The term, unless specifically defined by a crack size (depth, length), normally implies the appearance of a small crack, readily identifiable with the unaided eye, that because of its current size, has begun to influence the macroscopic engineering stress-strain response of an otherwise smooth, axially-loaded, laboratory fatigue specimen. Often there is little fatigue life remaining to complete specimen separation once the initiated crack becomes noticeable. Many investigations of the low-cycle fatigue resistance of engineering alloys utilize complete separation as the definition of fatigue life. This life is referred to as the crack initiation life. Close examination of the fatigue fractured surface would reveal distinct striations marking nearly every cycle of microscopic fatigue crack propagation that would then account for the majority of the specimen life. This is especially so in low-cycle fatigue testing. Models that accurately deal with the propagation of microscopic sized cracks, especially under high-temperature creep-fatigue-environmental interaction conditions (McDowell and Miller (1991)) are still under development. Such models are used in the establishment of engineering fatigue crack initiation behavior and are thus included in this review.

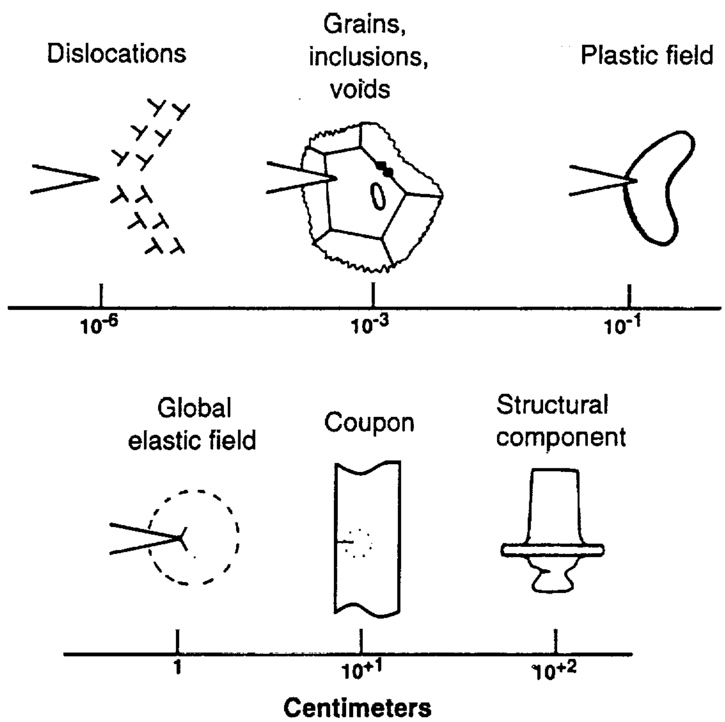

Figure 2 - Observational scales for cracking

MODEL EVOLUTION

In the earliest years of high-temperature structural durability prediction, the only concern with fatigue was for endurance limits in the very high cycles-to-failure regime (greater than about one million). Only mechanical fatigue loading at rather high frequencies was of concern, and efforts were devoted to reducing the magnitude of the excitations. Prior to the 1950's, there was no attempt to predict fatigue life -- only a concern that high-cycle fatigue may or may not occur. This greatly simplified the task of predicting structural life. Durability lifetimes, however, were calculated on the basis of time to failure as a result of creep-rupture phenomena. For this reason, creep-rupture became a commonly accepted means of inexpensively testing and judging a material's resistance to high-temperature operation. Simple, conservative procedures evolved that assumed, for pressure vessel design, for example, that the internal pressure acted continuously at its maximum value at maximum temperature for the entire duration of high-temperature usage. No credit was taken for operational time at lower temperatures or lower pressures (the time-fraction rule of Robinson (1952) was the first attempt to refine this simplistic approach). This simple bounding procedure was easy to put into practice using elastic strength of materials analyses. So long as designs could be built and operated economically while meeting these stringent requirements, there was little concern for developing more realistic life assessment methods. This simplistic view was accompanied by necessarily large factors of safety. However, durability problems persisted.

Pressure vessels did rupture prematurely and for a variety of reasons: poor quality control over material and fabrication techniques; intervention of corrosion and oxidation not considered in the original durability calculations; improper usage of the equipment by poorly trained operators; poor structural analysis procedures; intervention of thermal stresses and thermal fatigue; and a host of other parasitic causes about which the designer was ignorant or had little control. In addition, there was the continual desire to extend the useful lifetime of expensive equipment. There was virtually no acknowledgement of the complex technological problems of thermal stresses and thermal fatigue. No consideration was given to cyclic creep, creep-fatigue interactions, or attendant complex interaction with an active, aggressive environment.

It was nearly a decade after the identification (Manson (1953) and Coffin (1954)) of the plastic strain range power law for low-cycle fatigue that proposals were made for predicting structural lives in terms of both creep-rupture and cyclic strain fatigue, i.e., creep-fatigue (Taira (1962)). In the decade of the 1970's, there was rapid expansion of the number of creep-fatigue-environmental life assessment models being proposed. Although the rate of proposals declined in the 1980's, the degree of sophistication increased to keep pace with advancements in structural analysis techniques and corresponding increases in understanding of basic micromechanisms. The vast majority of the methods, once proposed, have seen little or no followup. From the standpoint of effort put forth toward their development, three basic methods stand out: 1) the time- and cycle-fraction rule as used in ASME Nuclear Code Case N-47; 2) the continuum damage mechanics approach of ONERA in France; and 3) the Strainrange Partitioning method of NASA Lewis. Each has sustained continual refinement owing to the support and continuity of the sponsoring organizations. The latter two have received the greatest attention during the last decade.

0 - VIRTUALLY NON-EXISTENT BEFORE WWII

0 - THE SECOND INDUSTRIAL REVOLUTION
- RAILROAD BRAKING
- PRESSURE VESSELS & PIPING
- IC ENGINE POPPET VALVES
- HIGH-TEMPERATURE FORMING DIES
- AERONAUTICAL GAS TURBINES
- NUCLEAR REACTORS
- REUSABLE ROCKET ENGINES
- SOLDERED LEAD-LESS CHIPS

0 - "BUILD-EM & BUST-EM" TOO EXPENSIVE (TIME & DOLLARS)

0 - STRUCTURAL ANALYSIS TECHNIQUES NOW AVAILABLE TO SUPPORT LOCAL STRESS-STRAIN KNOWLEDGE REQUIRED OF LIFE PREDICTION MODELS

0 - CRACK INITIATION "VALID" FOR DESIGN CALCULATIONS

Figure 3 - The drivers in historic evolution of high-temperature fatigue life prediction models

CLASSIFICATION OF METHODS

The large number of life prediction methods are classified in the following somewhat arbitrary categories. The thirteen categories are listed A through M below. Many methods fall into more than one category. The early linear damage (LDR) rules for fatigue are listed because they formed an important base for subsequent high-temperature life prediction methods. In Figs. 5-17 the first column refers to the categories appropriate to each method and the second column lists a three-letter shorthand notation for each method.

A - LIFE OR DAMAGE FRACTION RULES

B - STRESS-LIFE DIAGRAMS

C - FREQUENCY EFFECT EQUATIONS

D - STRAINRANGE - LIFE MODELS

E - DAMAGE MECHANICS

F - HYSTERESIS ENERGY MODELS

G - DUCTILITY EXHAUSTION

H - MICROCRACK GROWTH

I - STRAINRANGE PARTITIONING

J - MACRO-PHENOMENOLOGICAL MODELS

K - DAMAGE RATE MODELS

L - CYCLIC DAMAGE ACCUMULATION MODELS

M - MICROMECHANISTIC MODELS

Figure 4 - Classification of fatigue life prediction methods into thirteen overlapping categories

A - LIFE OR DAMAGE FRACTION RULES

The life- or damage-fraction rules are perhaps the most basic of all life prediction models. These rules simply state that when the fraction sums to a critical value, a crack or cracks instantaneously appear and failure has occurred. Earliest rules were linear in their summation of fractions to a value of unity at failure. Taira (1962) was the first to add time fractions (creep damage) to cycle fractions (fatigue damage) to represent creep-fatigue interaction. Wood (1966) proposed one of the first nonlinear summations of life fractions to obtain a nonlinear creep-fatigue interaction. A number of different fractional rules evolved as a result of using a different parameter (stress, strain, energy, etc.) to correlate with life (cycles-to-failure, time-to-rupture, etc.). The most widely used models listed below are the linear damage rule (Palmgren-Langer-Miner) for fatigue and the ASME Boiler and Pressure Vessel Code Case 1331 (currently updated and designated N-47) for high-temperature creep-fatigue interaction. In the latter, the damage is summed in a bi-linear fashion to a value of 1.0 <u>or less</u>, depending upon alloy and relative amounts of creep and fatigue fractions. Over half of the models below are listed under additional categories.

A	LDR	Linear Damage Rule/Palmgren (1924)
A	LDR	Linear Damage Rule/Langer (1937)
A	LDR	Linear Damage Rule/Miner (1945)
A	LCR	Linear Creep Rupture Damage Rule/Robinson (1952)
A	LCF	Linear Creep Damage/Berkovits (1961)
A	TCF	Time + Cycle Fraction Rule/Taira (1962)
A	LFA	Life Fraction Approach/D. S. Wood (1966)
AD	TPR	Ten Percent Rule/Manson & Halford (1967)
ABD	LCD	Linear Creep Damage for Thermal Fatigue/Spera (1968)
ABD	MLF	Modified Life Fraction Rule/Manson, Halford & Spera (1971)
ABD	LFR	Life Fraction Rule/ASME Code Case 1331 (pre-N-47) (1971)
ABD	TCD	Turbine Component Design/Timo (1971)
ABD	ITC	Interactive Time-Cycle Frac/Lagneborg & Attermo (1971)
ABD	RCF	Relaxation Creep Fatigue/Marshall & Cook (1971)
A	TCD	Time-Cycle Diagram/Esztergar & Ellis (1971)
ABE	CDC	Cumulative Damage Under Creep/Bui-Quoc (1979)
ABDE	PFC	Phenomenological Fatigue Creep/Bui-Quoc & Biron (1982)
AE	FCD	Fatigue + Creep Damage Mechs./Plumtree & Lemaitre (1982)
A	FNC	French Nuclear Code/Anon. (1985)
ABDM	FCE	Fatigue-Creep-Env Model/Neu & Sehitoglu (1989a & 1989b)
ABE	DDM	Differential Damage Mechanics/Arnold & Kruch (1991)

Figure 5 - Life prediction models based on life-fraction or damage-fraction concepts

B - STRESS-LIFE DIAGRAMS

The very first fatigue equations were written in terms of applied cyclic stresses, an approach well suited for classical high-cycle fatigue wherein the material responds in a nominally elastic manner. Since stress was also the primary parameter used to measure creep-rupture resistance, it was only natural that the first attempts to represent creep-fatigue damage were done on what came to be known as stress range diagrams. These plots related fatigue strength on one axis, creep-rupture strength on the other, with connecting families of lines each representing a different time to failure. Fatigue cycling frequencies associated with these diagrams were rather high. Cyclic lives were determined from knowledge of the time-to-failure and the frequency. Many years passed before these approaches fell into disuse and were replaced with models of a more general nature. Application of stress-based creep-rupture curves to the computation of creep damage during low-cycle isothermal and thermal fatigue began to appear in the late 1960s and early 1970s. In fact, the ASME Boiler and Pressure Vessel Code Case N-47 utilizes this approach for computation of creep damage during creep-fatigue loading under isothermal and thermal fatigue conditions. The damage mechanics approaches utilize stress-life diagrams for both creep and fatigue as the basic material failure diagrams for use in assessing damage during creep-fatigue cycling. Because of the very strong dependency of time-to-rupture on applied stress, computed lives are highly sensitive to the accuracy of magnitudes of the stresses computed from structural analyses. This excess sensitivity provided impetus to examine strain-based life prediction models.

B	SRD	Stress Range Diagrams/Lazan (1949)
B	SRD	Stress Range Diagrams/Forrest (1950)
ABD	LCD	Linear Creep Damage for Thermal Fatigue/Spera (1968)
ABD	MLF	Modified Life Fraction Rule/Manson, Halford & Spera (1971)
ABD	LFR	Life Fraction Rule/ASME Code Case 1331 (pre-N-47) (1971)
ABD	TCD	Turbine Component Design/Timo (1971)
ABD	ITC	Interactive Time-Cycle Frac/Lagneborg & Attermo (1971)
ABD	RCF	Relaxation Creep Fatigue/Marshall & Cook (1971)
ABE	CDC	Cumulative Damage Under Creep/Bui-Quoc (1979)
ABDE	PFC	Phenomenological Fatigue Creep/Bui-Quoc & Biron (1982)
ABDM	FCE	Fatigue-Creep-Environment Model/Neu & Sehitoglu (1989)
ABE	DDM	Differential Damage Mechanics/Arnold & Kruch (1991)

Figure 6 - Life prediction models based on stress-life diagrams

C - FREQUENCY EFFECT EQUATIONS

A common way to represent the amount of time under active stressing at temperature during fatigue cycling is through the frequency of cycling. Frequency-dependent fatigue lives of lead cable sheathing tested at room temperature were noted by Eckel as the decade of the 1950's began. While a number of different models have been proposed that utilize frequency as a principal parameter, the most famous have been the contributions of Dr. Coffin in association with the General Electric R&D Center. Rather complex equations resulted when attempts were made to use frequency as a means of capturing creep-fatigue effects during thermomechanical fatigue cycling. Ad hoc rules were developed to cover the widely varying creep-fatigue response of different alloy systems. Despite the attractiveness of using frequency as a simple metric for assessing the time-dependent complex interactions of fatigue with creep and oxidation, frequency-effect high-temperature fatigue models have not seen widespread usage.

C	FEE	Frequency Effect Equation/Eckel (1951)
C	TTF	Time To Failure Model/Coles & Skinner (1965)
CD	MCS	Method of Characteristic Slopes/Berling & Conway (1969)
CD	FMF	Frequency Modified Fatigue/Coffin (1970)
C	HTE	Hold Time Effects Model/Wellinger & Sautter (1973)
C	FSM	Frequency Separation Method/Coffin (1976)
CF	THE	Tensile Hysteresis Energy Model/Ostergren (1976a & 1976b)
CF	MTE	Mod Tensile Hyst Energy Model/Ostergren & Krempl (1979)
C	EFE	Endochronic Frequency Equation/Valanis (1981)

Figure 7 - Life prediction models based on frequency as a primary variable

D - STRAINRANGE - LIFE MODELS

In the early 1950's, high-performance industrial applications demanded attention from the design community. Electric power generation plants were being designed for higher use temperatures and efficiencies, aeronautical gas turbine engines had to have high performance and low weight, and such equipment did not have to have a nominally infinite design life. These circumstances set the stage for interest in high-strain, low-cycle fatigue. Stress no longer correlated well with fatigue life in the nonlinear, low-cycle, finite-life regime. The historically and physically significant plastic strain power law of low-cycle fatigue was proposed in 1953 and was developed subsequently into what is now known as the Manson-Coffin Law of low-cycle fatigue. For room temperature fatigue, it was soon recognized that plastic strain, while an excellent physically correct parameter, was not a convenient entity for designers to use. At the time, inelastic structural analysis was just in its infancy. To overcome this limitation, the total mechanical strain range (plastic plus inelastic) was correlated with low-cycle fatigue life in the early 1960's. A particularly significant model incorporating total strain range was the Method of Universal Slopes (MUS) that resulted from the intensive low-cycle fatigue research at the Lewis Research Center of the National Aeronautics and Space Administration. This method, published in 1965, is widely used for estimating the low-cycle fatigue resistance of materials in the absence of cyclic data. The fatigue properties used in the design of the Space Shuttle main engines were, for the most part, estimated by the method of universal slopes. Many models, even for high-temperature conditions wherein creep and environmental interaction are influential, are now based on total strain range versus life equations.

D	PSF	Plastic Strain Fatigue Law/Manson (1953)
D	PSF	Plastic Strain Fatigue Law/Coffin (1954)
D	TSR	Total Strain Range - Life Model/Manson & Hirschberg (1964)
D	MUS	Method of Universal Slopes/Manson (1965)
AD	TPR	Ten Percent Rule/Manson & Halford (1967)
D	TSR	Total Strain Range - Life Model/Morrow (1968)
ABD	LCD	Linear Creep Damage for Thermal Fatigue/Spera (1968)
D	PST	Plastic Strainrange Time Model/Berling & Conway (1969)
CD	FMF	Frequency Modified Fatigue/Coffin (1970)
CD	MCS	Method of Characteristic Slopes/Berling & Conway (1970)
DJ	TCE	Thermal Cycling Equation/Udoguchi & Wada (1971)
ABD	MLF	Modified Life Fraction Rule/Manson, Halford & Spera (1971)
ABD	LFR	Life Fraction Rule/ASME Code Case 1331 (pre-N-47) (1971)
ABD	TCD	Turbine Component Design/Timo (1971)
ABD	ITC	Interactive Time-Cycle Frac/Lagneborg & Attermo (1971)
ABD	RCF	Relaxation Creep Fatigue/Marshall & Cook (1971)
D	MSE	Modified Strainrange Equation/Sunamoto et al (1974)
D	TDE	Time Dependent Exponent of Strain/Udoguchi et al (1974)
ABDE	PFC	Phenomenological Fatigue Creep/Bui-Quoc & Biron (1982)
DF	OCF	Overstress Concept of Creep-Fatigue/Morishita et al (1988)
ABDM	FCE	Fatigue-Creep-Environment Model/Neu & Sehitoglu (1989)

Figure 8 - Models based on strain range as dominant cyclic variable

E - DAMAGE MECHANICS

Continuum Damage Mechanics has gained considerable interest over the past two decades through the aggressive efforts of Dr. Louis Chaboche and numerous colleagues at the French Space Agency (ONERA). The listing below represents but a small fraction of the large number of publications on the subject (numbering in the hundreds). Through personnel exchanges between ONERA and the NASA Lewis Research Center, NASA also has been contributing to the development of this powerful mathematical representation of fatigue damage, creep damage, and their manner of accumulation. A summary of the numerous significant contributions in the area of continuum damage mechanics has been published recently (Arnold and Kruch (1991)).

In the most basic of terms, the approach views damage as being volumetrically distributed in a uniform, homogeneous manner (hence the description, continuum mechanics). Its influence is to reduce the effective cross-sectional area available for carrying applied load, hence, steadily increasing the average stresses as damage increases. Failure is calculated to occur when a critical damage is reached. The method treats fatigue damage and creep damage on a common basis so that the two types of damage can be added directly.

E	DMC	Damage Mechanics for Creep/Kachanov (1958)
E	CDM	Continuum Damage Model/Lemaitre & Chaboche (1973)
E	CDM	Cyclic Damage Model/Lemaitre & Plumtree (1978)
ABE	CDC	Cumulative Damage Under Creep/Bui-Quoc (1979)
AE	FCD	Fatigue + Creep Damage Mechs./Plumtree & Lemaitre (1982)
ABDE	PFC	Phenomenological Fatigue Creep/Bui-Quoc & Biron (1982)
ABE	DDM	Differential Damage Mechanics/Arnold & Kruch (1991)

Figure 9 - Life prediction models based on classical damage mechanics

F - HYSTERESIS ENERGY MODELS

A logical extension of stress-based and strain-based low-cycle fatigue life prediction models is to examine the product of these two correlating variables, i.e., strain energy. The product of the stress and the plastic strain ranges is proportional to the plastic strain hysteresis energy that is expended per unit volume of material during a complete cycle. This is a scalar quantity that, upon initial consideration, might be deemed useful in correlating fatigue lives under states of multiaxial stresses and strains. This concept, however, has not fulfilled its promise, and little is gained by using this slightly more complex parameter over a strain-based parameter. Each is related to cyclic life in about the same manner. Whatever fatigue lives can be correlated with hysteresis energy can also be correlated with a simpler strain range parameter to within the same degree of accuracy. The vast majority (greater than 99.9%) of the plastic strain hysteresis energy imposed upon a volume of material during its fatigue life is converted to heat energy which in turn is dissipated to the surroundings. The dissipation process is akin to the heat generated by the friction of two sliding solids. Hysteresis energy models have been adapted for high-temperature creep-fatigue conditions. Again, however, they do not seem to offer any advantage above and beyond what can be obtained with strain range-based approaches.

F	HEA	Hysteresis Energy Approach/Morrow (1960)
CF	THE	Tensile Hysteresis Energy Model/Ostergren (1976a & 1976b)
FI	PEM	Partitioned Energy Model/Leis (1977)
CF	MTE	Mod Tensile Hyst Energy Model/Ostergren & Krempl (1979)
FH	CTE	Crack Tip Energy Model/Radhakrishnan (1980 & 1982)
F	CEG	Constant Enthalpy Gain Approach/Whaley (1983)
FI	SEP	Strain Energy Partitioning/He et al (1983)
DF	OCF	Overstress Concept of Creep-Fatigue/Morishita et al (1988)
F	CAB	Coated Anisotropic Blade Model/Nissley et al (1991)

Figure 10 - Life prediction models based on concept of hysteresis energy

G - DUCTILITY EXHAUSTION

Following on the heels of the Manson-Coffin equation for plastic strain low-cycle fatigue, ductility exhaustion models were proposed for both time-independent plasticity and time-dependent creep strains. The models are rather basic and are easy to understand at the layman level. They do require the ability to calculate small incremental amounts of inelastic deformation, a task that was not possible with any degree of accuracy for the early structural analysis computer codes. Even today, the reliability of computations of small ratcheting increments leaves a lot to be desired. The latest unified viscoplastic constitutive models do an excellent job of qualitative description, but require calibration to be able to match specific problems and achieve quantitative accuracy. None of the ductility exhaustion models have been used in any extensive way for calculating lifetimes of structural components.

G	DEM	Ductility Exhaustion Model/Manson (1960)
G	LDE	Linear Creep Ductility Exhaustion/Edmunds & White (1966)
G	DET	Ductility Exh for Thermal Fatigue/Polhemus et al (1973)
G	CPE	Creep-Plasticity Ductility Exh./Priest & Ellison (1981)
G	LPC	Linear Plastic-Creep Strain Exh./D.A. Miller et al (1982)
G	CPE	Creep-Plastic Exh/Priest, Beauchamp & Ellison (1983)
G	MDE	Modified Ductility Exhaustion Model/Hales (1983)

Figure 11 - Life prediction models based on concept of ductility exhaustion

H - CRACK GROWTH

It may at first appear contradictory that cyclic crack growth is listed as a category under fatigue crack initiation. However, it must be recognized that cracks associated with macrocrack initiation do not instantaneously appear. Rather, these short cracks physically grow to their size through a somewhat continuous microcrack growth process. On rare occasions, macrocrack growth behavior, as measured on specimens with long cracks, has been extrapolated into the small crack regime with acceptable results. In general, however, such extrapolation has not been satisfactory. The impetus for development of crack growth models is based on the desire to treat the problem in a more physically-correct manner. Indeed, cracks are generated from initial microscopic atomic level defects in metallic crystalline structures, and these cracks grow in size on a cycle-by-cycle evolutionary basis. The models considered herein are ones proposed for use in predicting fatigue lives of what are best referred to as crack initiation specimens. They were not intended for use in prediction of macroscopic, large crack growth behavior of structural components. A considerable number of these models have been proposed on a continuing basis since the Tompkins model of 1968. The listing below notes many such models, but it should not be considered as thorough and complete. To the best of the author's knowledge, none of the models have been adopted for use in structural engineering design.

H	CGM	Crack Growth Model/Tomkins (1968)
H	HCG	High Temp Crack Growth/Wareing, Tomkins & Sumner (1973)
H	CPM	Crack Propagation Model/Carden (1973)
H	CGA	Crack Growth Approach/Solomon (1973)
H	ETC	Elevated Temperature Crack Propagation/Tomkins (1975)
H	CCT	Creep Crack Tip Model/Wareing (1977)
H	CCD	Cyclic Creep Damage Model/Franklin (1978)
H	CIM	Crack Interaction Model/Janson (1979)
DH	MCI	Macro Crack Init, Fracture Mechs/Taira et al (1979)
HM	LCT	Local Crack Tip Model/Saxena (1981)
FH	CTE	Crack Tip Energy Model/Radhakrishnan (1982 & 1983)
HJM	FAM	FATIGMOD/A. Miller (1983)
H	CFC	Creep Fatigue Cracks Model/Riedel (1983)
H	SCC	Short Crack Creep Fatigue/Renner et al (1989)
HM	MMM	Microcracking, Creep-Fat-Envir/McDowell & Miller (1991)

Figure 12 - Life prediction models based on crack growth concepts

I - STRAINRANGE PARTITIONING

The Strainrange Partitioning (SRP) concept for representing high-temperature creep-fatigue interaction and life prediction has evolved into a comprehensive, workable engineering approach. From its revolutionary introduction in 1971 by Manson, Halford, and Hirschberg, the approach has been developed on a continuing basis through the uninterrupted sponsorship and efforts of the Lewis Research Center of the National Aeronautics and Space Administration (NASA). The titles of the major advances in the method's development are listed below and are good brief descriptors of these sub-elements of the SRP method. As seen from a cursory examination, the SRP method has been developed to deal with all of the major conditions expected during elevated temperature usage. These entail environmental interactions, mean stress effects, multiaxiality of stress and strain, thermal cycling, nonlinear cumulative damage, statistical representations, and representation in terms of total strain range rather than just the inelastic strain. Various industrial design usage has been made of the model, including the design of aeronautical gas turbine engine combustor liners. Software for implementation of the Total Strain Version of SRP is being made available to the general public through the COSMIC organization. The method is currently being evaluated for use in predicting thermal fatigue lives of thermally loaded structural components of the National Aero Space Plane (NASP). Aspects of the method are also being applied to advanced fiber-reinforced metal and intermetallic matrix composites for high-temperature aerospace structural components.

I	SRP	Strainrange Part/Manson, Halford & Hirschberg (1971)
Ia	IDR-SRP	Interaction Damage Rule, SRP/Manson (1973)
Ib	PDR-SRP	Product Damage Rule, SRP/Annis et al (1976)
Ic	ITF-SRP	Inelastic Thermal Fat, SRP/Halford & Manson (1976)
Id	DEX-SRP	Linear Ductility Exh., SRP/Manson & Halford (1976)
Ie	PWA-SRP	Pratt & Whitney Combustor, SRP/Vogel et al (1976)
If	MAF-SRP	Multiaxiality Factor, SRP/Manson & Halford (1977)
Ig	DNE-SRP	Ductility Normalized Eqs, SRP/Halford et al (1977)
Ih	SRC-SRP	Strainrange Conversion Prin, SRP/Manson (1979 & 1983)
Ii	MSE-SRP	Mean Stress Effects, SRP/Halford & Nachtigall (1980)
Ij	CEP-SRP	Combustion Engineering Model, SRP/Lawton (1982)
Ik	TSV-SRP	Total Strain Version of SRP/Halford & Saltsman (1983)
Il	DEP-SRP	Diesel Engine Piston, SRP/Saugerud (1983)
Im	NDR-SRP	Nonlinear Damage Rule, SRP/Hoffelner et al (1983)
In	SDA-SRP	Statistical Data Analysis, SRP/Wirsching (1984)
Io	SRL-SRP	Statistically Refined Life, SRP/Bicego (1984)
Ip	ETM-SRP	Exposure Time Modified, SRP/Kalluri & Manson (1985)
Iq	SSC-SRP	Steady-State Creep Rate, SRP/Kalluri et al (1987)
Ir	TFM-SRP	Time To Failure Modified SRP/Solomon (1988)
Is	TMF-SRP	Thermomech Fatigue, TSV-SRP/Saltsman & Halford (1988)
It	FMB-SRP	Fracture Mechs Basis of SRP/Kitamura & Halford (1989)
FI	PEM	Partitioned Energy Model/Leis (1977)
FI	SEP	Strain Energy Partitioning/He et al (1983)

Figure 13 - Life Prediction models based on variations of the method of strainrange partitioning

J - MACRO-PHENOMENOLOGICAL MODELS

This category represents those high-temperature fatigue crack initiation models that utilize phenomenological descriptors at the macroscopic level. While there are guiding reasons for selection of the phenomenological variables, some of the models assembled the variables in an empirically driven manner, i.e., what combination of the phenomenological variables will give the "best fit" to the available experimental results. A notable exception to this philosophy is the FATIGMOD of Miller (1983). The Miller model, which underwent considerable development, follows a highly rational approach that was based on considerable understanding of the sequences in the fatigue process. In this category, FATIGMOD and the CDA models are the most highly developed and would stand the greatest chance of being implemented into engineering design and use for structural life prediction.

DJ	TCE	Thermal Cycling Equation/Udoguchi & Wada (1971)
J	PHF	Parametric High Temperature Fatigue/Krempl (1971)
J	SST	Stress-Strain-Temperature Empirical Model/Bernstein (1979)
HJM	FAM	FATIGMOD/A. Miller (1983)
JL	PDA	Preliminary Cyclic Damage Accumulation/Moreno (1985)
J	ICC	Internal Cracking, Coated Single Xtal/Miner et al (1988)
JL	CDA	Cyclic Damage Accumulation/Nelson et al (1992)

Figure 14 - Life prediction models based on macro-phenomenological considerations

K - DAMAGE RATE MODELS

This category of high-temperature fatigue crack initiation life prediction models adopts an interesting perspective for dealing with time-dependent damage accumulation. The basic premise is that if time-dependent damage is being done, and it is more damaging than time-independent damage, then the slower is the rate of application of damage, the greater is the net affect of the damage. In other words, the slower the rate of application of the damaging parameter (inelastic strain, stress, energy, etc.) the greater will be the damage per cycle, and hence the lower will be the cyclic life. Considerable effort went into the development of the Majumdar and Maiya (1976 and 1980) approach at the Argonne National Laboratories. The driver for the research and development efforts was the requirement for life assessment, in advance of construction and usage, of nuclear power plants for electricity generation. The author is unaware of any current application of the listed damage rate models to engineering structural design.

K	DRM	Damage Rate Model/Majumdar & Maiya (1976)
K	MDR	Modified Damage Rate Model/Majumdar & Maiya (1980)
K	ILP	Incremental Life Prediction Law/Satoh & Krempl (1982)
K	TSM	Temp. & Strain Rate Model/Zhang et al (1990)

Figure 15 - Life prediction models based on damage rate concepts

L - CYCLIC DAMAGE ACCUMULATION MODELS

This category is limited because of the uniqueness of the assumptions that originally went into the development of the first cyclic damage accumulation model. The reader is referred to Moreno's 1985 account for a full justification of the assumptions. Beyond the original assumptions, however, the model takes on more of the character of the MACRO PHENOMENOLOGICAL MODELS described earlier. The model was developed by engineers at the Pratt & Whitney Commercial Engineering Division of United Technologies Corporation, East Hartford, CT, under sponsorship of the NASA Lewis Research Center's Hot Section Turbine Engine Technology Program (HOST). The method has been transcribed into a PC-compatible computer code and is being made commercially available through the COSMIC organization. It is one of only two high-temperature creep-fatigue life prediction computer programs being made available to the general public through COSMIC. The other is the Total Strain Version of Strain Range Partitioning.

JL	PDA	Preliminary Cyclic Damage Accumulation/Moreno (1985)
JL	CDA	Cyclic Damage Accumulation/Nelson et al (1992)

Figure 16 - Life prediction models based on a unique assumption of cyclic damage accumulation

M - MICROMECHANISTIC MODELS

As the micromechanisms of high-temperature cyclic deformation and damage become more widely known and documented through use of advanced metallurgical investigative tools, the more models will be created to describe these physical effects. For the most part, the models proposed to date are highly specific to the alloy systems and cyclic circumstances studied. The most generalized of the models are those of Miller (1983), Neu and Sehitoglu (1989a and 1989b), and McDowell and Miller (1991). The two Millers are unrelated.

M	GBS	Grain Boundary Sliding Model/McLean & Pineau (1978)
M	RVG	R-Void Growth Model/Min & Raj (1978)
M	OCC	Oxide Cracking/Challenger et al (1981a & 1981b)
M	SOC	Stress-Oxidation Crack Tip Model/Antolovich et al (1981)
HM	LCT	Local Crack Tip Model/Saxena (1981)
M	GBV	Grain Boundary Void Model/Weertman (1982)
M	IGW	Init and Growth of Wedge Cracks/Baik & Raj (1982a & 1982b)
M	OFI	Oxidation Fatigue Interaction Model/Reuchet & Remy (1983)
M	ARN	Anelastic Recovery, ODS Alloys/Nardone (1983)
HJM	FAM	FATIGMOD/A. Miller (1983)
M	CCC	Critical Cavity Criteria Model/Rie et al (1988)
M	CBS	Cohesive Boundary Strength Model/Romanoski et al (1988)
M	GBO	Grain Boundary Oxidation Model/Oshida & Liu (1988)
ABDM	FCE	Fatigue-Creep-Envir Model/Neu & Sehitoglu (1989a & 1989b)
HM	MMM	Microcracking, Creep-Fat.-Envir./McDowell & Miller (1991)

Figure 17 - Life prediction models based on micromechanistic observations and descriptions

MOST HIGHLY DEVELOPED MODELS

The vast majority of the methods, once proposed, have seen little or no followup. From the standpoint of effort put forth toward their development, three basic methods stand out: 1) the time- and cycle-fraction rule as used in ASME Nuclear Code Case N-47; 2) the continuum damage mechanics approach of ONERA in France; and 3) the Strainrange Partitioning Method of NASA Lewis. Each has sustained continual refinement owing to the support and continuity of the sponsoring organizations. The latter two have received the greatest attention during the last decade. The review presented is a severe condensation of a more extensive review being prepared by the author for a monograph on the topic of high-temperature fatigue life prediction methodology for cyclic crack initiation of materials.

0 - TIME-FRACTION + CYCLE-FRACTION
- ASME CODE, USA

0 - CONTINUUM DAMAGE MECHANICS
- ONERA, FRANCE
- NASA-LEWIS, USA

0 - STRAINRANGE PARTITIONING
- NASA-LEWIS, USA

Figure 18 - Three models are the most highly developed

REFERENCES

Annis, C. G., VanWanderham, M. C. and Wallace, R. M., Strainrange Partitioning Behavior of an Automotive Turbine Alloy, NASA CR-134974, 1976.

Anon., Section III ASME Boiler and Pressure Vessel Code Case 1331-5 (predecessor of current Code Case N-47), 1971.

Anon., Design and Construction Rules for Mechanical Components of Fast Breeder Reactor Nuclear Islands, RCC-MR. Association Francaise pour les regles de conception et de construction des materiels des chaudieres electro-nucleaires, France, 1985.

Antolovich, S. D., Liu, S. and Baur, R., "Low Cycle Fatigue Behavior of Rene' 80 at Elevated Temperature," Metallurgical Transactions A, Vol. 12A, 1981, pp. 473-481.

Arnold, S. M. and Kruch, S., Differential Continuum Damage Mechanics Models for Creep and Fatigue of Unidirectional Metal Matrix Composites, NASA TM-105213, 1991.

Baik, S. and Raj, R., "Wedge Type Creep Damage in Low Cycle Fatigue," Metallurgical Transactions A, Vol. 13A, 1982, pp. 1207-1214.

Baik, S. and Raj, R., "Mechanisms of Creep-Fatigue Interactions," Metallurgical Transactions A, Vol. 13A, 1982, pp. 1215-1221.

Berkovits, A., Investigation of Three Analytical Hypotheses for Determining Material Creep Behavior Under Varied Loads, NASA TN-D-799, 1961.

Berling, J. T. and Conway, J. B., "A Proposed Method for Predicting Low-Cycle Fatigue Behavior of 304 and 316 Stainless Steel," Transactions of the Metallurgical Society, AIME, Vol. 245, 1969, pp. 1137-1140.

Berling, J. T. and Conway, J. B., "A New Approach to the Prediction of Low-Cycle Fatigue Data," Metallurgical Transactions, Vol. 1, 1970, pp. 805-809.

Bernstein, H., "A Stress-Strain-Time Model (SST) for High Temperature Low Cycle Fatigue," in Methods for Predicting Material Life in Fatigue, W. J. Ostergren and J. R. Whitehead (eds.), ASME, NY, 1979, pp. 89-100.

Bicego, V., "A Nonstandard Technique for the Evaluation of the Basic Laws of the Strain Range Partitioning Method in Creep-Fatigue Life Prediction," in Proceedings, Second International Conference on Fatigue and Fatigue Thresholds (Fatigue 84), C. J. Beevers (ed.), Engineering Materials Advisory Services, Ltd., Cradley Heath, Warley, U.K., Vol. 3, 1984, pp. 1257-1268.

Bui-Quoc, T., "An Engineering Approach for Cumulative Damage in Metals Under Creep Loading," Transactions, ASME, Journal of Pressure Vessel Technology, Vol. 101, 1979, pp. 337-343.

Bui-Quoc, T. and Biron, A., "A Phenomenological Approach for the Analysis of Combined Fatigue and Creep," Nuclear Engineering Design, Vol. 71, 1982, pp. 89-102.

Carden, A. E., "Parametric Analysis of Fatigue Crack Growth," in Proceedings, Conference on Creep and Fatigue in Elevated Temperature Environment, Philadelphia, PA, Sept. 1973 (Sheffield, England, April 1974). Sponsored by the American Society for Testing and Materials, Philadelphia, and the Institute of Mechanical Engineers, London, 1974.

Challenger, K. D., Miller, A. K. and Brinkman, C. R., "An Explanation for the Effects of Hold Periods on the Elevated Temperature Fatigue Behavior of 2 1/4Cr-1Mo Steel," Journal of Engineering Materials and Technology, ASME, Vol. 103, 1981, pp. 7-14.

Challenger, K. D., Miller, A. K. and Langdon, R. L., Journal of Materials and Energy Systems, Vol. 3, 1981, pp. 51-61.

Chan, K. S. and Miller, A. K., "FATIGMOD: A Unified Phenomenological Model for Predicting Fatigue Crack Initiation and Propagation," ASME International Conference on Advances in Life Prediction Methods, 1983, pp. 1-16.

Coffin, L. F., "A Study of the Effects of Cyclic Thermal Stresses on a Ductile Metal," Transactions, ASME, Vol. 76, 1954, pp. 931-950.

Coffin, L. F., "The Effect of Frequency on High-Temperature, Low-Cycle Fatigue," in Proceedings, Air Force Conference on Fracture and Fatigue of Aircraft Structures, AFDL-TR-70-144, 1970, pp. 301-312.

Coffin, L. F., "The Concept of Frequency Separation in Life Prediction for Time-Dependent Fatigue," ASME-MPC Symposium on Creep-Fatigue Interaction, MPC-3, 1976, pp. 349-363.

Coles, A. and Skinner, D., "Assessment of Thermal-Fatigue Resistance of High Temperature Alloys," Journal of the Royal Aeronautical Society of London, Vol. 69, 1965, pp. 53-55.

Eckel, J. F., "Influence of Frequency on the Repeated Bending Life of Acid Lead," Proceedings, American Society for Testing and Materials, Vol. 51, 1951, pp. 745-756.

Edmunds, H. G. and White, D. J., "Observations of the Effect of Creep Relaxation on High-Strain Fatigue," Journal of Mechanical Engineering Science, Vol. 8, No. 3, 1966, pp. 310-321.

Esztergar, E. P. and Ellis, J. R., "Cumulative Fatigue Damage Concepts in Creep-Fatigue Life Predictions," in Proceedings, International Conference on Thermal Stresses and Thermal Fatigue, D. J. Littler (ed.), The Butterworth Group, London, 1969, pp. 128-156.

Franklin, C. J., High-Temperature Alloys for Gas Turbines, D. Coutsouradis, P. Felix, H. Fischmeister, L. Habraken, Y. Lindblom and M. O. Speidel (eds.), Applied Science, London, 1978, pp. 513-547.

Hales, R., "A Method of Creep Damage Summation Based on Accumulated Strain for the Assessment of Creep-Fatigue Endurance," Fatigue of Engineering Materials and Structures, Vol. 6, No. 2, 1983, pp. 121-135.

Halford, G. R. and Manson, S. S., "Life Prediction of Thermal-Mechanical Fatigue Using Strainrange Partitioning," in Thermal Fatigue of Materials and Components, ASTM STP 612, D. A. Spera and D. F. Mowbray (eds.), 1976, pp. 239-254.

Halford, G. R., Saltsman, J. F. and Hirschberg, M. H., "Ductility Normalized-Strainrange Partitioning Life Relations for Creep-Fatigue Life Prediction," in Proceedings, Conference on Environmental Degradation of Engineering Materials, Virginia Polytechnic Institute and State University, Blacksburg, VA, 1977, pp. 599-612.

Halford, G. R. and Nachtigall, A. J., "The Strainrange Partitioning Behavior of an Advanced Gas Turbine Disk Alloy, AF2-1DA," Journal of Aircraft, Vol. 17, No. 8, 1980, pp. 598-604.

Halford, G. R. and Saltsman, J. F., "Strainrange Partitioning - A Total Strainrange Version," ASME International Conference on Advances in Life Prediction, D. A. Woodford and J. R. Whitehead (eds.), 1983, pp. 17-26.

He, J., Duan, Z., Ning, Y. and Zhao, D., "Strain Energy Partitioning and Its Application to GH33A Nickel-Base Superalloy and 1Cr18Ni9Ti Stainless Steel," in Advances in Life Prediction Methods, D. A. Woodford and J. R. Whitehead (eds.), ASME, NY, 1983, pp. 27-32.

Hoffelner, W., Melton, K. N. and Wuthrich, C., "On Life Time Predictions with the Strain Range Partitioning Method," Fatigue of Engineering Materials and Structures, Vol. 6, No. 1, 1983, pp. 77-87.

Janson, J., "Damage Model of Creep-Fatigue Interaction," Engineering Fracture Mechanics, Vol. 11, 1979, pp. 397-403.

Kachanov, L. M., "Time of the Rupture Process Under Creep Conditions," Izvestiia Akademii Nauk, SSSR, Otdelenie Tekhnicheskikh Nauk., No. 8, 1958, pp. 26-31.

Kalluri, S. and Manson, S. S., Time Dependency of SRP Life Relationships, NASA CR-174946, 1985.

Kalluri, S., Manson, S. S. and Halford, G. R., "Environmental Degradation of 316 Stainless Steel in High Temperature Low Cycle Fatigue," in Third International Conference on Environmental Degradation of Engineering Materials, R. P. McNitt and M. R. Louthan, Jr. (eds.), Pennsylvania State University, University Park, PA, 1987, pp. 503-519.

Kalluri, S., Manson, S. S. and Halford, G. R., "Exposure Time Considerations in High Temperature Low Cycle Fatigue," in Proceedings, Fifth International Conference on Mechanical Behavior of Materials (ICM-5, Beijing), M. G. Yan, S. H. Zhang and Z. M. Zheng (eds.), Pergamon Press, Vol. 2, 1987, pp. 1029-1036.

Kitamura, T. and Halford, G. R., High Temperature Fracture Mechanics Basis for Strainrange Partitioning, NASA TM-4133, 1989.

Krempl, E., "The Temperature Dependence of High-Strain Fatigue Life at Elevated Temperature in Parameter Representation," in Proceedings, International Conference on Thermal Stresses and Thermal Fatigue, D. J. Littler (ed.), The Butterworth Group, London, 1971, pp. 36-46.

Lagneborg, R. and Attermo, R., "The Effect of Combined Low-Cycle Fatigue and Creep on the Life of Austenitic Stainless Steels," Metallurgical Transactions, Vol. 2, 1971, pp. 1821-1827.

Langer, B. F., "Fatigue Failure From Stress Cycles of Varying Amplitude," Transactions, ASME, Vol. 59, 1937, pp. A160-A162.

Lawton, C. W., "Use of Low-Cycle Fatigue Data for Pressure Vessel Design Low-Cycle Fatigue and Life Prediction," ASTM STP-770, C. Amzallag, B. N. Leis, P. Rabbe (eds.), 1982, pp. 585-599.

Lazan, B. J., "Dynamic Creep and Rupture Properties Under Tensile Fatigue Stress," in Proceedings, American Society for Testing and Materials, Vol. 49, 1949, p. 757.

Leis, B. N., "An Energy-Based Fatigue and Creep-Fatigue Damage Parameter," Transactions, ASME, Journal of Pressure Vessel Technology, Vol. 99, 1977, pp. 524-533.

Lemaitre, J., Chaboche, J. L. and Munakata, Y., "Method of Metal Characterization for Creep and Low Cycle Fatigue Prediction in Structures - Example of Udimet 700," in Proceedings, Symposium on Mechanical Behavior of Materials, Kyoto, Japan, 1973, pp. 239-249.

Lemaitre, J. and Plumtree, A., Joint ASME/CSME PVP Conference, Montreal, 1978.

Levaillant, C., Rezgui, B. and Pineau, A., Proceedings, Third International Conference on Mechanical Behavior of Materials, Cambridge, England, Miller and Smith (eds.), Vol. 2, 1979, pp. 163-173.

Majumdar, S. and Maiya, P. S., "A Damage Equation for Creep-Fatigue Interaction," 1976 ASME-MPC Symposium on Creep-Fatigue Interaction, MPC-3, ASME, NY, 1976, pp. 323-336.

Majumdar, S. and Maiya, P. S., "A Mechanistic Model for Time-Dependent Fatigue," Journal of Engineering Materials and Technology, ASME, Vol. 102, 1980, pp. 159-167.

Manson, S. S., Behavior of Materials Under Conditions of Thermal Stress, NACA TN-2933, 1954.

Manson, S. S., "Thermal Stress in Design, Part 19, Cyclic Life of Ductile Materials," Machine Design, Vol. 32, 1960, pp. 139-144.

Manson, S. S. and Hirschberg, M. H., "Fatigue Behavior in Strain Cycling in the Low- and Intermediate-Cycle Range," in Fatigue - An Interdisciplinary Approach, Burke, Reed and Weiss (eds.), Syracuse University Press, NY, 1964, pp. 133-178.

Manson, S. S., "Fatigue: A Complex Subject - Some Simple Approximations," Experimental Mechanics, Vol. 5, No. 7, 1965, pp. 193-226.

Manson, S. S. and Halford, G. R., "A Method of Estimating High-Temperature Low-Cycle Fatigue Behavior of Materials," in Proceedings, International Conference on Thermal and High-Strain Fatigue, Metals and Metallurgy Trust, London, 1967, pp. 154-170.

Manson, S. S., Halford, G. R. and Hirschberg, M. H., "Creep-Fatigue Analysis by Strain-Range Partitioning," Symposium on Design for Elevated Temperature Environment, ASME, NY, 1971, pp. 12-28.

Manson, S. S., Halford, G. R. and Spera, D. A., "The Role of Creep in High Temperature Low-Cycle Fatigue," Chapter 12, Advances in Creep Design, A. I. Smith and A. M. Nicolson (eds.), Halsted Press, 1971, pp. 229-249.

Manson, S. S., "The Challenge to Unify Treatment of High Temperature Fatigue - A Partisan Proposal Based on Strainrange Partitioning," in Fatigue at Elevated Temperatures, ASTM STP-520, A. E. Carden, A. J. McEvily and C. H. Wells (eds.), 1973, pp. 744-782.

Manson, S. S. and Halford, G. R., "Treatment of Multiaxial Creep-Fatigue by Strainrange Partitioning," 1976 MPC Symposium on Creep-Fatigue Interaction, MPC-3, R. M. Curran (ed.), 1976, pp. 299-322.

Manson, S. S. and Halford, G. R., Discussion to paper by J. J. Blass and S. Y. Zamrik entitled, Multiaxial Low-Cycle Fatigue of Type 304 Stainless Steel in 1976 ASME-MPC Symposium on Creep-Fatigue Interaction, ASME, NY, pp. 129-159. Journal of Engineering Materials and Technology, ASME, Vol. 99, 1977, pp. 283-286.

Manson, S. S., "Some Useful Concepts for the Designer in Treating Cumulative Fatigue Damage at Elevated Temperatures," Third International Conference on Mechanical Behavior of Materials, Cambridge, England, Vol. I, 1979, pp. 13-45.

Manson, S. S., "The Strainrange Conversion Principle for Treating Cumulative Fatigue Damage in the Creep Range," in Random Fatigue Life Prediction, Y. S. Shin and M. K. Au-Yang (eds.), PVP Vol. 72, ASME, NY, 1983, pp. 1-30.

Marshall, P. and Cook, T. R., "Prediction of Failure of Materials Under Cyclic Loading," in Proceedings, International Conference on Thermal Stresses and Thermal Fatigue, D. J. Littler (ed.), The Butterworth Group, London, 1971, pp. 81-88.

McDowell, D. L. and Miller, M. P., "Physically Based Microcrack Propagation Laws for Creep-Fatigue-Environment Interaction," presented at the ASME Winter Annual Meeting, Atlanta, GA, 1991.

McLean, D. and Pineau, A., "Grain-Boundary Sliding as a Correlating Concept for Fatigue Hold-Times," Metal Science, Vol. 12, 1978, pp. 313-316.

Miller, D. A., Hamm, C. D. and Phillips, J. L., "A Mechanistic Approach to the Prediction of Creep-Dominated Failure During Simulated Creep-Fatigue," Material Science and Engineering, Vol. 53, 1982, pp. 233-244.

Min, B. K. and Raj, R., "Hold-Time Effects in High Temperature Fatigue," Acta Metallurgica, Vol. 26, 1978, pp. 1007-1022.

Miner, M. A., "Cumulative Damage in Fatigue," Transactions, ASME, Journal of Applied Mechanics, Vol. 67, 1945, pp. A159-A167.

Miner, R. V., Gayda, J., Hebsur, M. G., "Creep-Fatigue Behavior of Ni-Co-Cr-Al-Y Coated PWA 1480 Superalloy Single Crystals," in Low Cycle Fatigue - Directions for the Future, ASTM STP-942, H. D. Solomon, G. R. Halford, L. R. Kaisand and B. N. Leis (eds.), 1988, pp. 371-384.

Morishita, M., Taguchi, K., Asayama, T., Ishikawa, A. and Asada, Y., "Application of the Overstress Concept for Creep-Fatigue Evaluation," in Low Cycle Fatigue - Directions for the Future, ASTM STP-942, H. D. Solomon, G. R. Halford, L. R. Kaisand and B. N. Leis (eds.), 1988, pp. 487-499.

Morrow, J., An Investigation of Plastic Strain Energy as a Criterion for Finite Fatigue Life, Report to the Garrett Corp., 1960.

Nelson, R. S., Levan, G. W. and Harvey, P. R., Creep Fatigue Life Prediction for Engine Hot Section Materials (Isotropic), NASA CR-189221, August 1992.

Neu, R. W. and Sehitoglu, H., "Thermomechanical Fatigue, Oxidation, and Creep: Part I. Damage Mechanisms," Metallurgical Transactions A, Vol. 20A, 1989, pp. 1755-1767.

Neu, R. W. and Sehitoglu, H., "Thermomechanical Fatigue, Oxidation, and Creep: Part II. Life Prediction," Metallurgical Transactions A, Vol. 20A, 1989, pp. 1769-1783.

Nissley, D. M., Meyer, T. G. and Walker, K. P., "Life Prediction and Constitutive Models for Engine Hot Section Anisotropic Materials Program," Final Report, NASA CR-189223, Sept. 1992.

Nordone, V. C., Doctoral Dissertation, Columbia University, NY, 1983.

Oshida, Y. and Liu, H. W., "Grain Boundary Oxidation and an Analysis of the Effects of Oxidation on Fatigue Crack Nucleation Life," in Low Cycle Fatigue - Directions for the Future, ASTM STP-942, H. D. Solomon, G. R. Halford, L. R. Kaisand and B. N. Leis (eds.), 1988, pp. 1199-1217.

Ostergren, W. J., "A Damage Function and Associated Failure Equations for Predicting Hold Time and Frequency Effects in Elevated Temperature, Low Cycle Fatigue," Journal of Testing and Evaluation, Vol. 4, No. 5, 1976, pp. 327-339.

Ostergren, W. J., "Correlation of Hold Time Effects in Elevated Temperature Low Cycle Fatigue Using a Frequency Modified Damage Function," 1976 ASME MPC Symposium on Creep-Fatigue Interaction, MPC-3, 1976, pp. 179-202.

Ostergren, W. J. and Krempl, E., "A Uniaxial Damage Accumulation Law for Time-Varying Loading Including Creep-Fatigue Interaction," Transactions, ASME, Journal of Pressure Vessel Technology, Vol. 101, 1979, pp. 118-124.

Palmgren, A., "Die Lebensdauer von Kugellagern," Z.V.D.I., Vol. 68, No. 14, 1924, pp. 339-341.

Plumtree, A. and Lemaitre, J., Advances in Fracture Research, D. Francois (ed.), Pergamon Press, NY, 1982, p. 2379.

Polhemous, J. F., Spaeth, C. E. and Vogel, W. H., "Ductility Exhaustion for Prediction of Thermal Fatigue and Creep Interaction," in Fatigue at Elevated Temperatures, ASTM STP-520, A. E. Carden, A. J. McEvily and C. H. Wells (eds.), 1973, pp. 625-636.

Priest, R. H. and Ellison, E. G., "A Combined Deformation Map - Ductility Exhaustion Approach to Creep-Fatigue Analysis," Materials Science and Engineering, Vol. 49, 1981, pp. 7-17.

Priest, R. H., Beauchamp, D. J. and Ellison, E. G., "Damage During Creep-Fatigue," in Advances in Life Prediction Methods, D. A. Woodford and J. R. Whitehead (eds.), ASME, NY, 1983, pp. 115-122.

Radhakrishnan, V. M., "Damage Accumulation and Fracture Life in High-Temperature Low-Cycle Fatigue," in Low-Cycle Fatigue and Life Prediction, ASTM STP-770, D. Amzallag, B. N. Leis and P. Rabbe (eds.), 1982, pp. 135-151.

Radhakrishnan, V. M., "Life Prediction in Time Dependent Fatigue," in Advances in Life Prediction Methods, D. A. Woodford and J. R. Whitehead (eds.), ASME, NY, 1983, pp. 143-150.

Renner, E., Vehoff, H. and Neumann, P., "Prediction for Creep-Fatigue Based on the Growth of Short Cracks," Fatigue and Fracture of Engineering Materials and Structures, Vol. 12, No. 6, 1989, pp. 569-584.

Reuchet, J. and Remy, L., "Fatigue Oxidation Interaction in a Superalloy - Application to Life Prediction in High Temperature Low Cycle Fatigue," Metallurgical Transactions A, Vol. 14A, 1983, pp. 141-149.

Rie, K. T., Schmidt, R. M., Ilschner, B. and Nam, S. W., "A Model for Predicting Low Cycle Fatigue Life Under Creep-Fatigue Interaction," in Low Cycle Fatigue - Directions for the Future, ASTM STP-942, H. D. Solomon, G. R. Halford, L. R. Kaisand and B. N. Leis (eds.), 1988, pp. 313-328.

Riedel, H., "Crack-Tip Stress Fields and Crack Growth Under Creep-Fatigue Conditions," in Elastic-Plastic Fracture, Second Symposium, Vol. 1, Inelastic Crack Analysis, ASTM STP-803, C. F. Shih and J. P. Guda (eds.), 1983, pp. 505-520.

Robinson, E. L., "Effect of Temperature Variation on the Long-Time Rupture Strength of Steels," Transactions, ASME, Vol. 74, No. 5, 1952, pp. 777-780.

Romanoski, G. R., Antolovich, S. D. and Pelloux, R. M., "A Model for Life Predictions of Nickel-Base Superalloys in High-Temperature Low Cycle Fatigue," in Low Cycle Fatigue - Directions for the Future, ASTM STP-942, H. D. Solomon, G. R. Halford, L. R. Kaisand and B. N. Leis (eds.), 1988, pp. 456-467.

Saltsman, J. F. and Halford, G. R., A Model for Life Prediction of Thermomechanical Fatigue Using the Total Strain Version of Strainrange Partitioning (SRP) - A Proposal, NASA TP-2779, 1988.

Satoh, M. and Krempl, E., "An Incremental Life Prediction Law for Creep-Fatigue Interaction," Pressure Vessels and Piping, Vol. 60, ASME, NY, 1982, pp. 71-79.

Saugerud, O. T., "Advances in Life Prediction of Thermally-Loaded Diesel Engine Components," in Advances in Life Prediction Methods, D. A. Woodford and J. R. Whitehead (eds.), ASME, NY, 1983, pp. 229-240.

Saxena, A., "A Model for Predicting the Effect of Frequency on Fatigue Crack Growth Behavior at Elevated Temperature," Fatigue of Engineering Materials and Structures, Vol. 3, No. 3, 1981, pp. 247-255.

Saxena, A., Landes, J. D. and Bassani, J. L. (eds.), Nonlinear Fracture Mechanics: Vol. I - Time-Dependent Fracture, ASTM STP-995, 1989.

Solomon, H. D., "Frequency Modified Low Cycle Fatigue Crack Propagation," Metallurgical Transactions, Vol. 4, 1973, pp. 341-347.

Solomon, H. D., "Low-Frequency, High-Temperature Low Cycle Fatigue of 60Sn-40Pb Solder," in Low Cycle Fatigue - Directions for the Future, ASTM STP-942, H. D. Solomon, G. R. Halford, L. R. Kaisand and B. N. Leis (eds.), 1988, pp. 342-370.

Spera, D. A., A Linear Creep Damage Theory for Thermal Fatigue of Materials, Doctoral Thesis, University of Wisconsin, Madison, WI, 1968.

Sunamoto, D., Endo, T. and Fujihara, M., "Hold Time Effects in High Temperature, Low Cycle Fatigue of Low Alloy Steels," in Creep and Fatigue in Elevated Temperature Applications, Institution of Mechanical Engineers, Vol. 1, 1974, C252.

Taira, S., "Lifetime of Structures Subjected to Varying Load and Temperature," Colloquium on Creep in Structures, Stanford University, Stanford, CA. International Union of Theoretical and Applied Mechanics (IUTAM), N. J. Hoff (ed.), Springer-Verlag, 1962, pp. 96-119.

Taira, S., Ohtani, R. and Komatsu, T., "Application of J - Integral to High-Temperature Crack Propagation, Part 1: Creep Crack Propagation," Transactions of ASME, Journal of Engineering Materials Technology, Vol. 101, 1979, pp. 154-161.

Tapsell, H. J., Forrest, P. G. and Tremain, G. R., "Creep Due to Fluctuating Stresses at Elevated Temperatures," Engineering, Vol. 170, 1950, p. 189.

Timo, D. P., "Designing Turbine Components for Low-Cycle Fatigue," Proceedings, International Conference on Thermal Stresses and Thermal Fatigue, D. J. Littler (ed.), The Butterworth Group, London, 1971, pp. 453-469.

Tomkins, B., "Fatigue Crack Propagation - An Analysis," Philosophical Magazine, Vol. 18, 1968, pp. 1041-1066.

Tomkins, B., "The Development of Fatigue Crack Propagation Models for Engineering Applications at Elevated Temperatures," ASME Journal of Engineering Materials and Design, Vol. 97, 1975, pp. 289-297.

Udoguchi, T. and Wada, T., "Thermal Effect on Low-Cycle Fatigue Strength of Steels," Proceedings, International Conference on Thermal Stresses and Thermal Fatigue, D. J. Littler (ed.), The Butterworth Group, London, 1971, pp. 109-123.

Udoguchi, T., Asada, Y. and Ichino, I., "A Frequency Interpretation of Hold-Time Experiments on High Temperature Low-Cycle Fatigue of Steels for LMFBR," Creep and Fatigue in Elevated Temperature Applications, Institution of Mechanical Engineers, Vol. 1, 1974, C211.

Valanis, K. C., "On the Effect of Frequency on Fatigue Life," Mechanics of Fatigue, AMD Vol. 47, Proceedings of a Symposium on Mechanics in Fatigue, Washington, D.C., T. Mura (ed.), ASME, NY, 1981, pp. 21-32.

Vogel, W. H., Soderquist, R. W. and Schlein, B. C., "Application of Creep-LCF Cracking Model to Combustor Durability Prediction," in Fatigue Life Technology, T. A. Cruse and J. P. Gallagher (eds.), ASME, NY, 1977, pp. 22-31.

Wareing, J., Tomkins, B. and Sumner, G., "Extent to Which Material Properties Control Fatigue Failure at Elevated Temperatures," in Fatigue at Elevated Temperatures, ASTM STP-520, American Society for Testing and Materials, Philadelphia, PA, 1973, pp. 123-138.

Wareing, J., "Creep-Fatigue Interactions in Austenitic Stainless Steels," Metallurgical Transactions A, Vol. 8A, 1977, pp. 711-721.

Weertman, J. R., "A Study of the Role of Grain Boundary Cavitation in the Creep-Fatigue Interaction in High Temperature Fatigue," Final Technical Report, Northwestern University, Evanston, IL, 1982.

Wellinger, K. and Sautter, S., "Der Einfluss von Tempertur, Dehnungsgeschwindigkeit and Haltezeit auf das Zeitfestigkeitsverhalten von Stahlen," Arck. Eisenhuttenwes, Vol. 44, 1973, pp. 47-55.

Whaley, P. W., "A Thermodynamic Approach to Material Fatigue," in Advances in Life Prediction Methods, D. A. Woodford and J. R. Whitehead (eds.), ASME, NY, 1983, pp. 41-50.

Wirsching, P. H. and Wu, Y. T., Reliability Considerations for the Total Strainrange Version of Strainrange Partitioning, NASA CR-174757, 1984.

Wood, D. S., "The Effect of Creep on the High-Strain Fatigue Behavior of a Pressure Vessel Steel," Welding Research Supplement, Vol. 45, 1966, pp. 90s-96s.

Zhang, A., Bui-Quoc, T. and Gomuc, R., "A Procedure for Low Cycle Fatigue Life Prediction for Various Temperatures and Strain Rates," submitted to Journal of Engineering Materials and Technology, 1990.